Columbia University
in the City of New York

LAMONT GEOLOGICAL OBSERVATORY
PALISADES, NEW YORK

Reduction of Deep Sea Refraction Data

Technical Report No. 1
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Lamont Geological Observatory

(Columbia University)

Palisades, New York

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by

Charles B. Officer

Paul C. Wuenschel

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Table of Contents

List of Figures

Reduction of Deep Sea Refraction Data

Charles B. Officer and Paul C. Wuenschel

I. Introduction

During the summer of 1950 an extensive two-ship deep sea refraction operation was made on Atlantis 164 and Caryn 17 cruises. A total of seventy refraction stations were made on tracks from Bermuda to Charleston, Norfolk to Bermuda, Bermuda to the Nares Deep, Bermuda to Halifax, and Halifax to Woods Hole. Again during the spring of 1951 the opportunity arose to make another two ship refraction operation on Atlantis 172 and Caryn 22 cruises. Thirty-three profiles were made covering the Caribbean, the Puerto Rico Trough, and a track from Puerto Rico to Bermuda to Woods Hole.

It has been necessary to make several corrections and reductions to the raw data in order to obtain the final values for the travel time plots. The method of reduction of the deep sea refraction data is not found in any of the standard geophysical texts, and that used in shallow water seismic work is not applicable. It has been necessary to devise new methods as the occasion arose. These methods of reduction are, in general, quite simple; but it has been thought advantageous to present them in this form for the benefit of and use in future investigations. Further it is hoped that this report results in a uniform method of

reducing deep sea refraction data. The several graphs that have been found helpful in carrying out the reductions have also been included in such a manner that they may be used directly from the report.

II. Shot Instant Correction

In a two ship refraction operation one ship, say the Atlantis, heaves to and lowers her hydrophones preparatory to receiving. The Caryn then proceeds on course shooting the necessary shots to make the profile. After completing the shooting, the Caryn heaves to and prepares to receive, as the Atlantis gets underway on course toward the Caryn, firing shots to complete the reverse profile.

The shot instant is picked up on the shooting ship and sent over the air to the receiving ship where it is recorded on the refraction record. Simultaneously, a shot record is made on the shooting ship. Several identifiable buzzes and signals are sent over the air after the shot and recorded on both the shot and refraction record in order to allow correlation of the two records and location of the shot instant on the refraction record when, due to poor radio contact or other causes, the shot instant is not recorded on the refraction record. Besides allowing this correlation the shot record is useful in determining the depth of the shot.

After locating the shot instant on the refraction record either by direct reading or by correlation with the

shot record, it is necessary to make a correction for the time it took the shot instant to travel from the shot point to the shooting ship (see Figure 1). In order to do this it is necessary to know the depth of the shot and the distance that the ship has traveled from the time the shot was thrown over the side to the time it detonated.

The distance that the ship has moved is obtained by multiplying the ship's speed by the time over the side. The time over the side is the interval from the instant the charge is thrown over the side to the instant of detonation. The depth of shot is read directly from the shot record. It

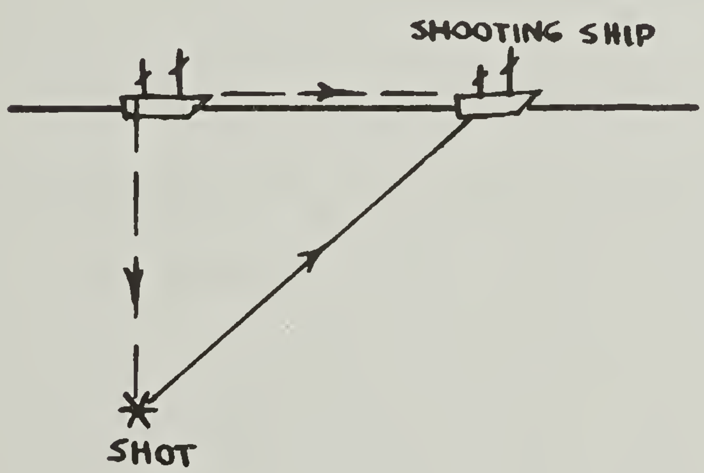


Fig. 1 Shot and Shooting Ship

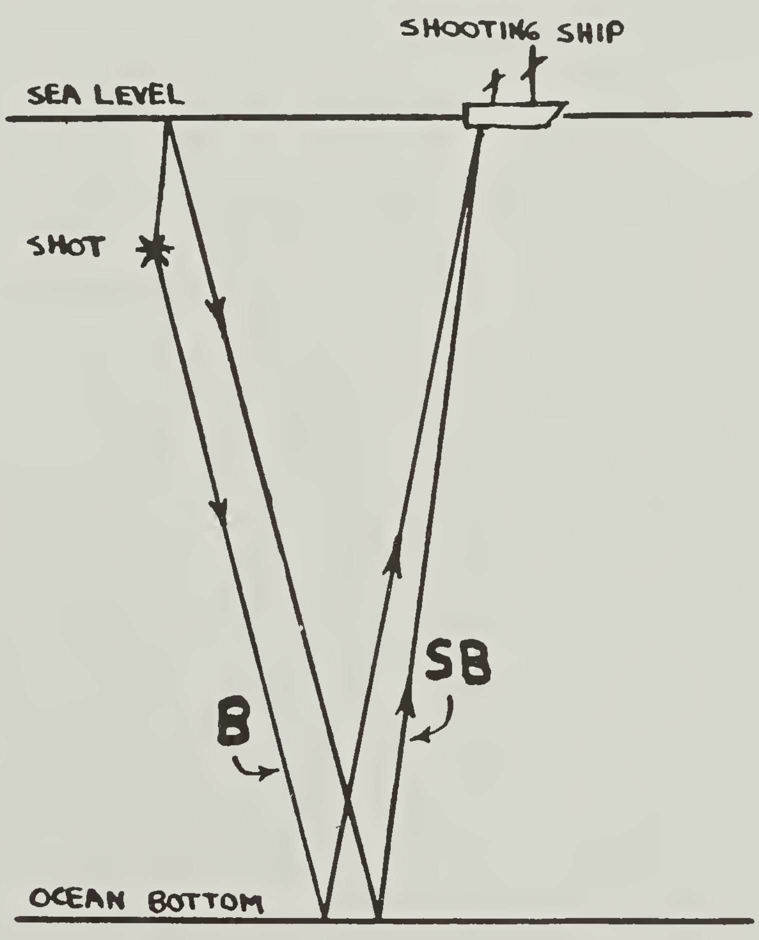


Fig. 2 Bottom and Surface-bottom Reflections

is equal to half the time difference between the bottom and the surface-bottom reflections for depths of water greater than 1000 fathoms (see Figure 2). It is then an easy matter to calculate, knowing the velocity of sound in the water from the bathythermograph observations, the time it took the shot instant to travel from the shot point to the shooting ship, i. e., the shot instant correction.

III. Sinking Rates of Explosive Charges

Unless the shot record is recorded photographically, it is not possible to read the bottom-surface bottom reflection interval with consistency; and even on some of the photographic records it is not possible to read this interval due either to blocking of the amplifier or excessive noise level. For these shots it is necessary to use the data from those shots on which this interval could be read. This is most easily done by referring to the sinking rate graphs (see Figures 3 - 12). These are plots of twice the depth of the explosion, i. e., the bottom-surface bottom interval, versus the time over the side. Knowing the time over the side the depth of the explosion can then be read off the graphs. The scatter of the plotted points about the line that is drawn is ± .01 second for the depth of the explosion. It can safely be assumed that any readings taken from these graphs will be accurate to that figure, in the range of the observed points.

All the charges that were used in plotting these points were fired by safety fuse. The charges consisting of

$\frac{1}{2}$ pound demolition blocks were prepared by taping or tying the blocks together. Sometimes $3\frac{1}{2}$ pound demolition blocks were used also. The 50 pound charges of demolition blocks were prepared by replacing the top and bottom of the 50 pound boxes by slats and removing all the wax paper. The Mk 42T charges were fired without the associated tail assembly, and the Mk 30 charges were fired with the tail assembly. The Mk 54 charges were fired in their carrying cases.

IV. Reduction to Surface of Reference

It is usually desirable to reduce the travel time data to a surface of reference from which to measure seismic depths. In the case of deep sea refraction profiles sea level is chosen as the most convenient surface of reference. The refraction, reflection, and direct wave travel times are corrected to bring them to this surface of reference. The correction to the first reflection is the time if would take sound in water to travel from A to B plus the time from C to D (see Figure 13). This is obtained by multiplying the depth of the shot plus the depth of the hydrophone, expressed in seconds, by cos θ, where θ is the angle of incidence of the reflected wave on the bottom. The correction for the second and third reflections is obtained in a similar manner. The correction for the refracted waves is equal to the product of the sum of these depths by the cosine of the angle (α) whose sine is the ratio of the average [redacted] water velocity ($\bar{c}$ [redacted]) to the velocity in the refracted layer (c_n). The correction for the

direct wave is negligable for most of the shots. (The ray paths for these various arrivals are shown in Figure 14.)

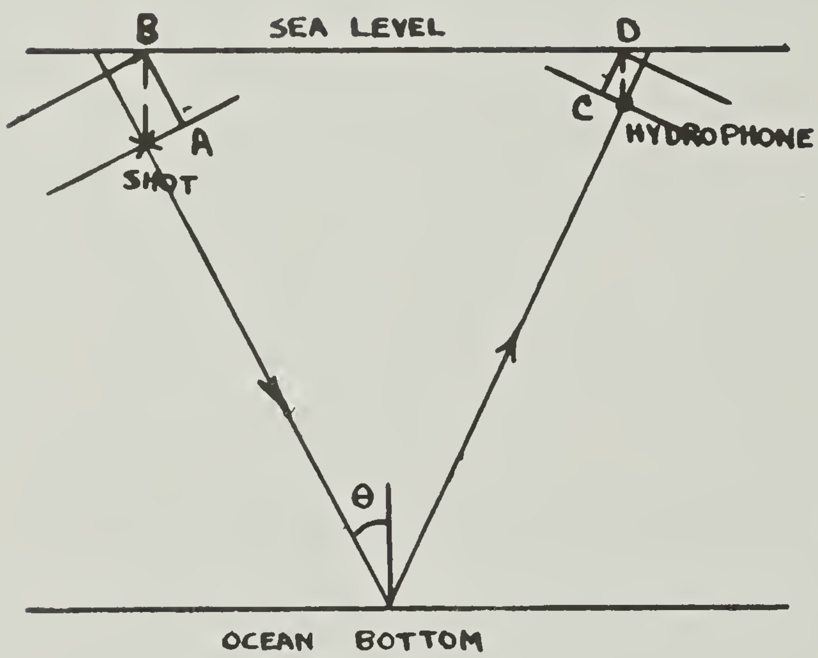


Fig. 13 Ray path for R_1

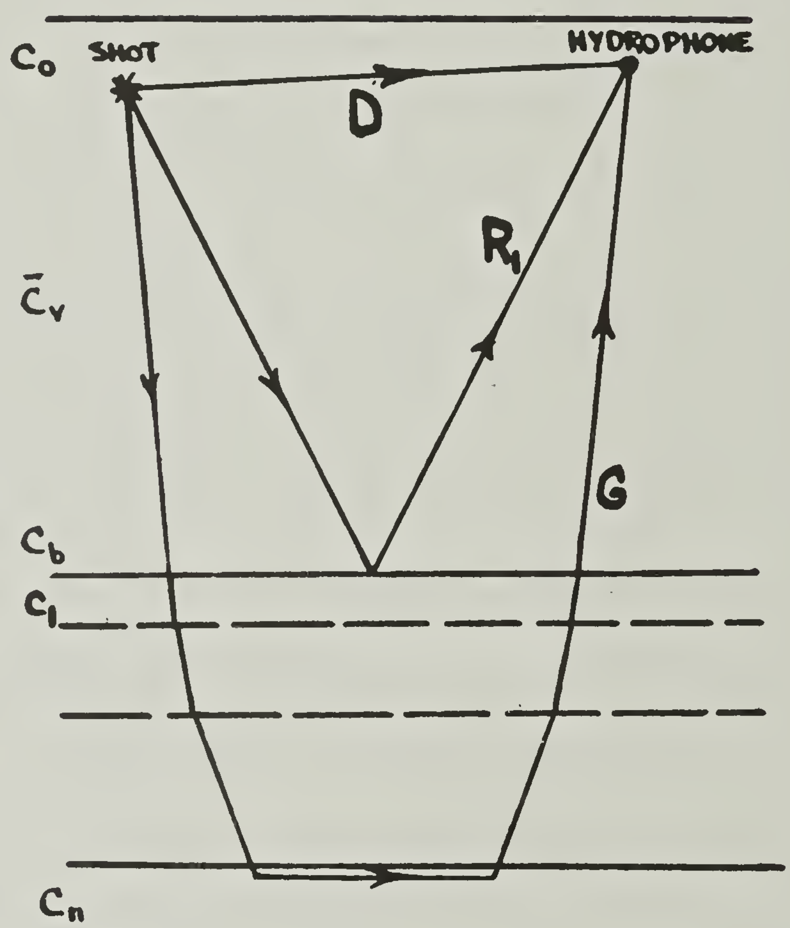


Fig. 14 Ray paths for D, R_1, and G

Figures 15 - 17 are graphs of cos θ verus direct wave travel time, i. e., range, for the first, second, and third reflections. The factor that is needed to multiply the sum of the depths of the shot and hydrophone can be read directly off this graph for the particular range involved. Figure 18 is a graph of cos α versus the ratio $c_n/\bar{c}_v$. From this graph the same factor can be read off for the refraction

arrivals. For all basement velocities that are obtained in deep sea refraction work, i. e., $c_n/\bar{c}_v$ greater than 4.0, this factor may be taken equal to unity.

V. Topographic Correction

Areas of moderate to small topography were chosen for most of the deep sea refraction profiles; but before any calculations of basement velocity or depth can be made, it is necessary to remove the small effects of the irregularities in the bottom topography on the refraction travel times. A mean depth of water is chosen, and corrections are made plus and minus about this depth for the travel times of refraction arrivals. Difficulty arises in choosing in what material the bottom topography takes place, whether it represents directly topography in the sediments or is a representation of the basement topography. The choice that is made depends on the type of topography and structure involved.

Figure 19 is a set of graphs of the corrections to be applied to the ground arrivals versus the difference in elevation of the bottom topography from the mean for various velocity contrasts between the material forming the bottom topography and the ocean.

VI. Curved Ray Paths

The time intercept for a refraction line in the simplest case of a single refracting layer is given by the approximate formula,

$$I = \frac{2H}{c_1 \bar{c}_v} \sqrt{c_1^2 - (\bar{c}_v)^2} \qquad (1)$$

where $\bar{c}_v$ is the "time average" of the sound velocity in water taken from sea level to the bottom. It is defined by the relation,

$$\bar{C}_v = \frac{H}{\int_0^H \frac{dh}{c_v}} \qquad (2)$$

and is that velocity which when multiplied by the vertical reflection time will give the true depth of water. Equation 1 is approximate because it takes an average vertical velocity for the water. It does not give the exact expression for the change in the intercept ray path due to the velocity structure in the water nor the change in time over this path. Calculations by Tolstoy and separately by Worzel and Officer show that the approximate formula is valid to 0.002 seconds for refraction velocities greater than 20,000 feet per second and is valid to 0.01 for velocities greater than 5600 feet per second at a depth of water of 2700 fathoms. Thus, it is concluded that the approximate formula can be used with negligable error for any deep sea basement calculations.

VII. Sound Velocities in the Ocean

For refraction calculations it is necessary to know surface sound velocity in water for the determination of range from the direct wave and the average vertical velocity for the determination of refraction depths. The surface sound velocity is determined from the bathythermographic observations taken along the shooting track and the surface

salinity, quoted in various oceanographic reports for the particular area and season involved. Sound velocity is not critically dependent on the variations observed in salinity so that with the bathythermographic observations that have been taken the surface sound velocity can usually be quoted to ± 2 feet per second. The average vertical velocity is obtained from "Tables of the Velocity of Sound in Pure Water and Sea Water," published by the Hydrographic Department, Admiralty, London (1939). A check on this value is obtained from the R^2 versus D^2 plots. These two values usually agree to ± 10 feet per second, but for the sake of uniformity the British Admiralty Table value is used in all refraction calculations.

VIII. Check Plots

In order to insure confidence in the data used in the travel time graphs, two check graphs are made. These are the R^2 versus D^2 and the navigation plots.

R_1^2, R_2^2, R_3^2,----plotted against D^2 will produce straight lines except for changes in depth or slope of the bottom. These graphs will then bring out any obvious errors that have been made in R or in D. The slope of this line is the square of the ratio $c_o/\bar{c}_v$, which gives a check on the value obtained from the British Admiralty Tables for $\bar{c}_v$. The value for $\bar{c}_v$ can not be read from this plot to better than ± 10 feet per second.

The navigation plot is a graph of time of day that

the charge was thrown over the side versus the direct wave travel time. This will also plot as straight line depending on the constancy of the ship's speed and course. Besides checking the value of D, this graph is useful in giving the velocity of the shooting ship when there is no pit log on that ship. Further, the navigation plot in conjunction with the ship's log gives the range of the reverse point when no shot was fired at this station.

IX. R_1 - D Versus R_1 Graphs

Depending on the thickness of the isothermal surface water layer, the direct wave is recorded from six to forty miles. On those refraction records for which there is no D present, R_1 is used to determine the range. In the laboratory the R_1^2 versus D^2 plots are used to find the range at short distances (less than 40 miles), and curved ray path calculations are used for the longer shots. However, at sea it is desirable to have a quicker method for the rough travel time plots. For this purpose the $R_1 - D$ versus R_1 curves are included (see Figure 20). Knowing the value of R_1 and the depth of the water, the expected time interval between R_1 and D can be read off the graph. These curves are not accurate for the longer shots because the velocity structure in the water becomes important, and the simple straight line, average velocity calculations are in error. These curves are plotted from the equation,

$$R_1 - D = \sqrt{\frac{C_0^2}{(\bar{C}_v)^2} D^2 + 4\frac{H^2}{(\bar{C}_v)^2}} - D. \quad (3)$$

X. Check List of Data Necessary for Complete Reduction

In general -

1. Ship's navigation.
2. Ship's log.
3. Miscellaneous data not appearing in ship's log such as distance and azimuth when shooting ship is abeam at beginning and end of reversed profile, time shooting ship is abeam, and propeller revolutions at time of each shot when no pit log or taffrail log is available.
4. Bathythermograph observations.

For each shot -

1. Charge size and fuse length.
2. Time of day the charge was thrown over the side.
3. Amount of time charge was over the side before detonation.
4. Depth of water under shot. (Also indicate shot on fathometer tape.)
5. Pit log speed and mileage.

Symbols used

c_o = surface sound velocity in the ocean

$\bar{c}_v$ = average vertical velocity of sound in the ocean

c_b = sound velocity at the bottom of the ocean

c_1 = velocity of compressional waves in the first refraction layer

c_n = velocity of compressional waves in the nth refraction layer

R_1 = travel time of the first reflected wave

R_2 = travel time of the second reflected wave

R_3 = travel time of the third reflected wave

R_m = travel time of the mth reflected wave

D = travel time of the direct wave

G = travel time of refraction arrival

B = bottom reflection time from the shot record

SB = surface-bottom reflection time from the shot record

ΔW = topographic correction

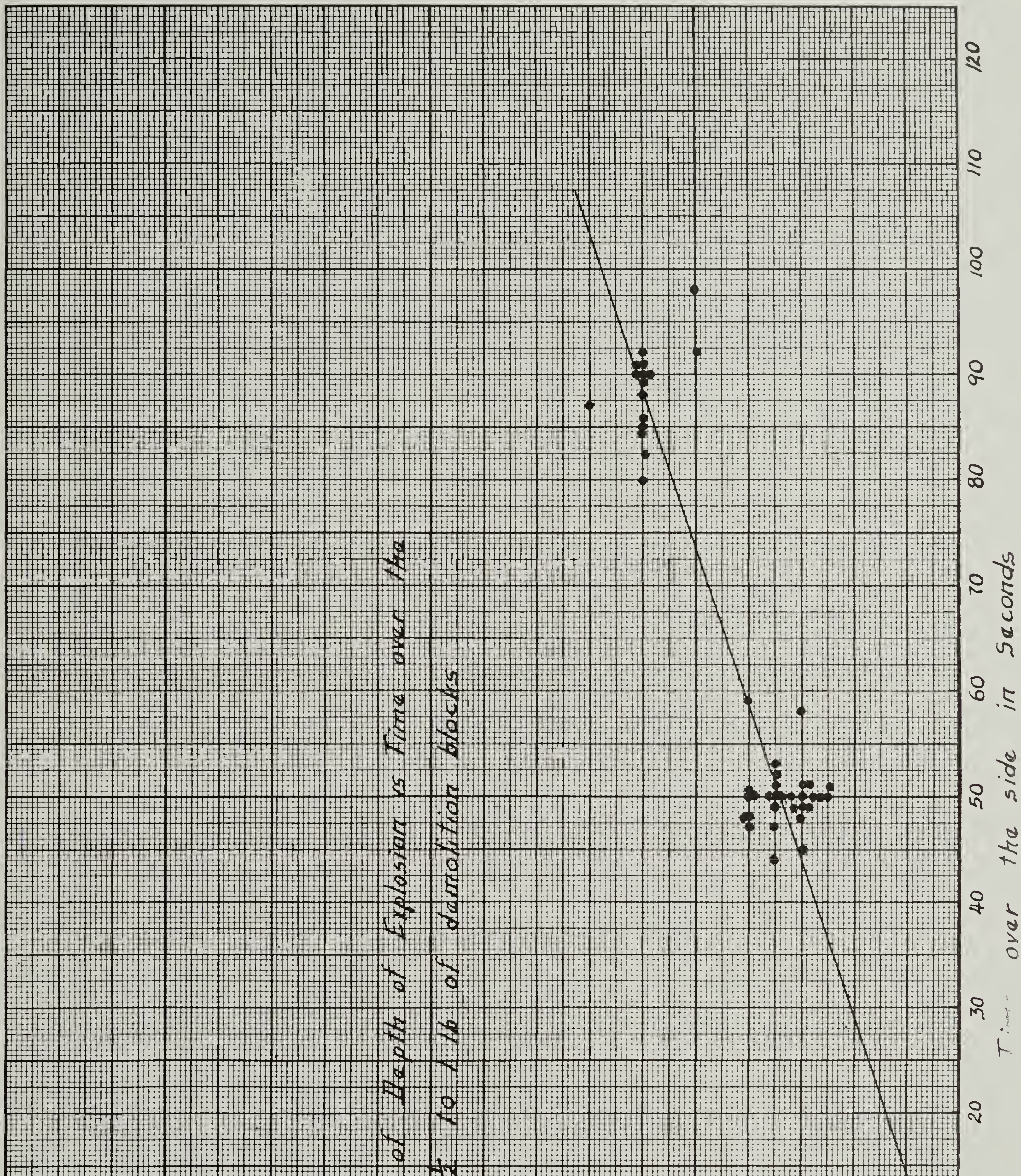
Δh = difference in elevation of the bottom from the mean

H = depth of the ocean

θ = angle of incidence of R_1 on bottom

α = angle of incidence of G on bottom

Figure 3



Graph of Depth of Explosion vs Time over the
side of 1/2 to 1 lb of demolition blocks
over the side in Seconds
Twice Depth of Explosion in Seconds
0
10
20
30
40
50
60
70
80
90
100
110
120
.02
.04
.06
.08

Figure 4

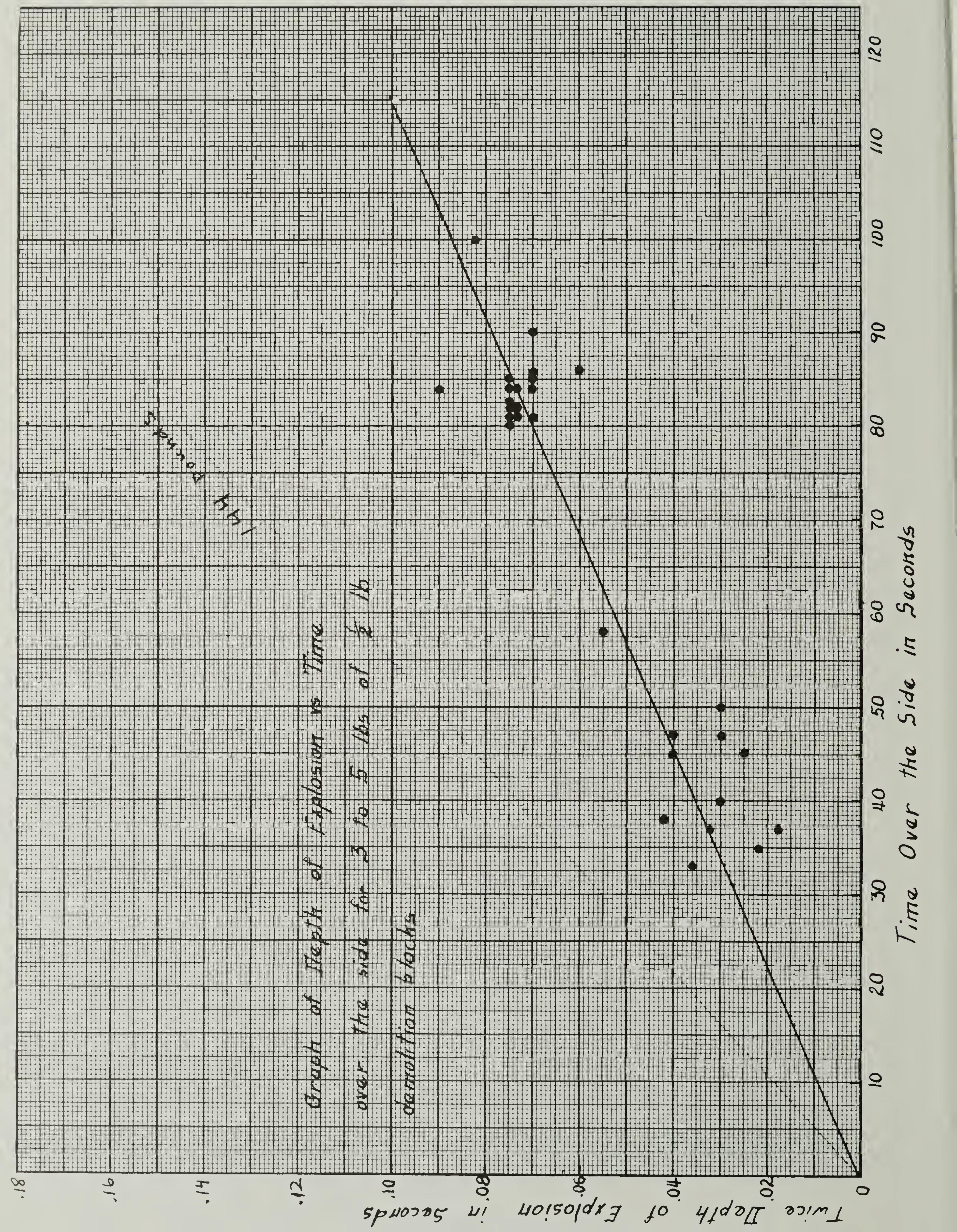
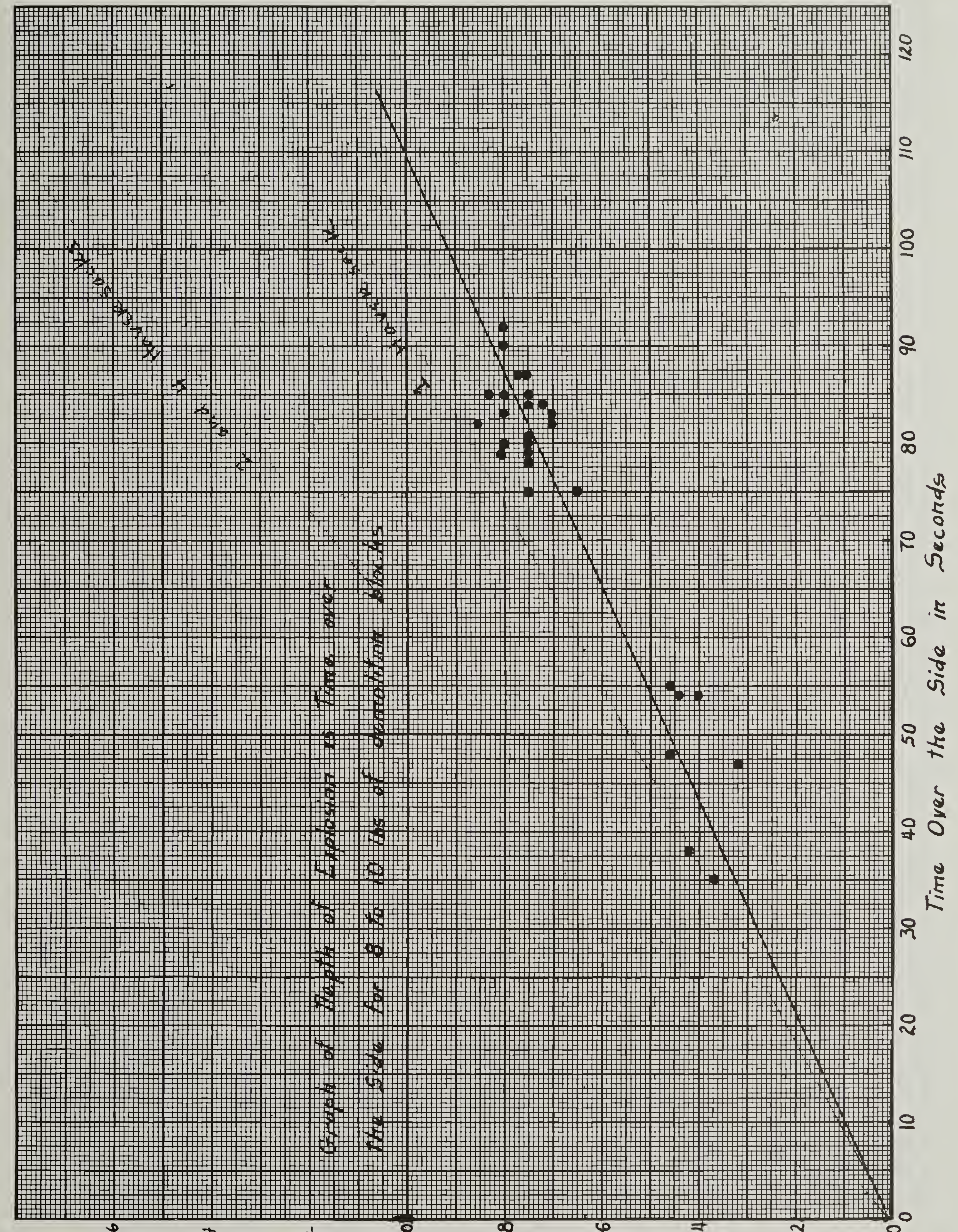

Graph of Depth of Explosion vs Time over the side for 3 to 5 lbs of ½ lb demolition blocks
144 Pounds
Time Over the Side in Seconds
Twice Depth of Explosion in Seconds
0
10
20
30
40
50
60
70
80
90
100
110
120
.02
.04
.06
.08
.10
.12
.14
.16
.18

Figure 5


Graph of Depth of Explosion to Time over
the Side for 8 to 10 lbs of demolition blocks
Time Over the Side in Seconds
0
10
20
30
40
50
60
70
80
90
100
110
120
Twice Depth of Explosion in Seconds
0
.02
.04
.06
.08
.10
.12
.14
.16

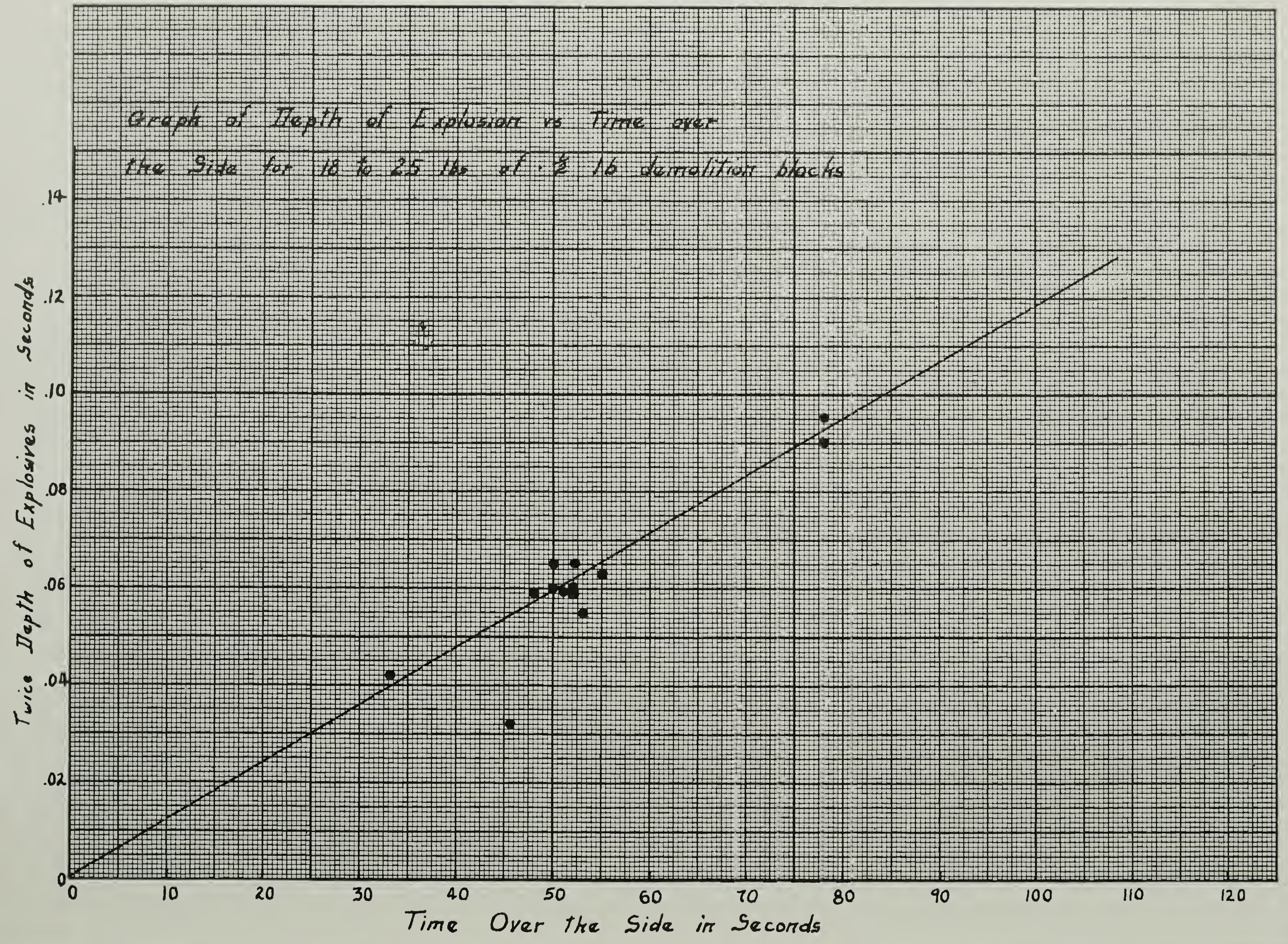

Graph of Depth of Explosion vs Time over
the Side for 18 to 25 lbs of ½ lb demolition blocks
Twice Depth of Explosives in Seconds
0
.02
.04
.06
.08
.10
.12
.14
0
10
20
30
40
50
60
70
80
90
100
110
120
Time Over the Side in Seconds

Figure 6

Figura 7

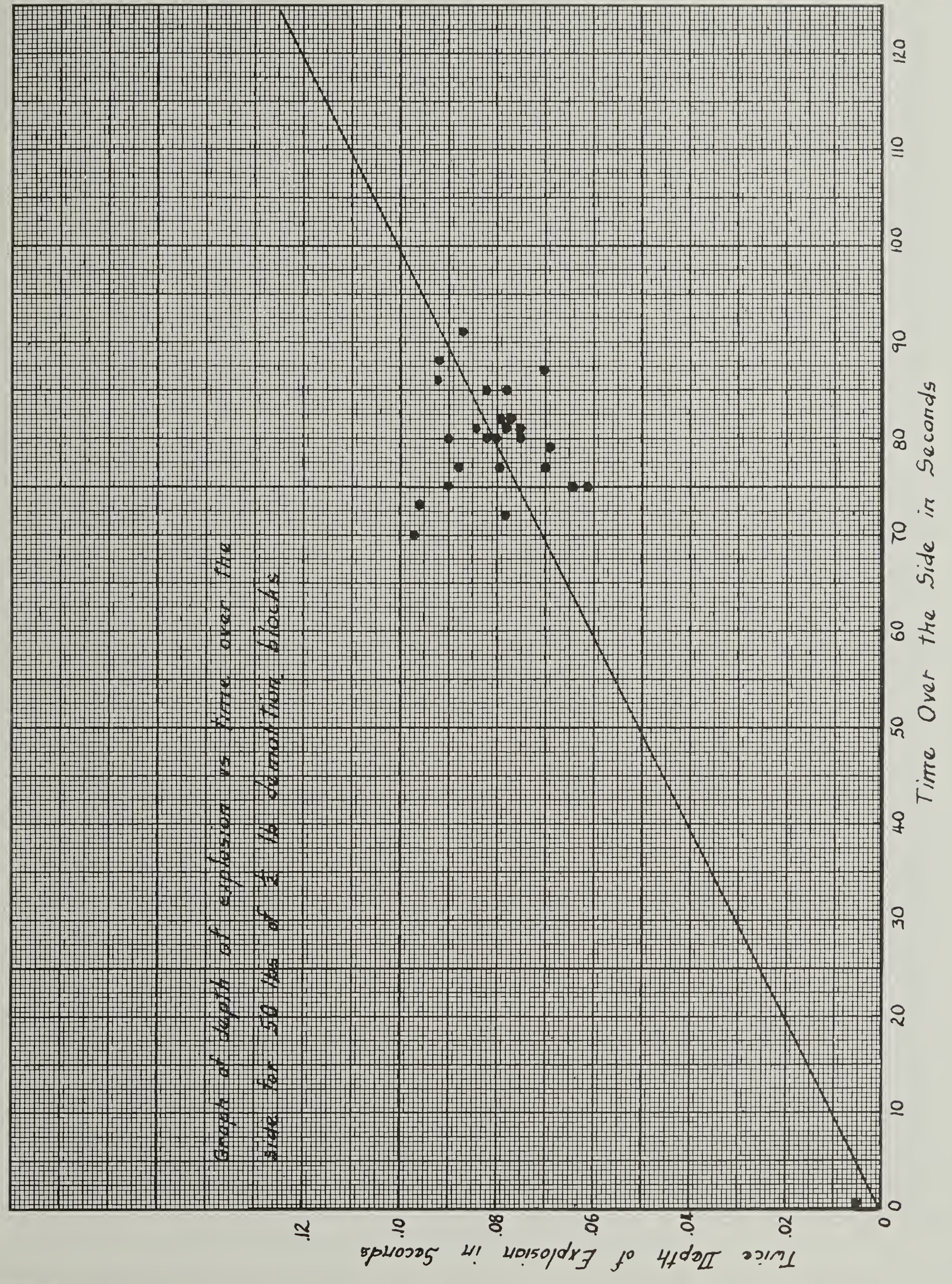

Graph of depth of explosion vs time over the side for 50 lbs of ½ lb demolition blocks
Time Over the Side in Seconds
0
10
20
30
40
50
60
70
80
90
100
110
120
Twice Depth of Explosion in Seconds
0
.02
.04
.06
.08
.10
.12

Figure 8

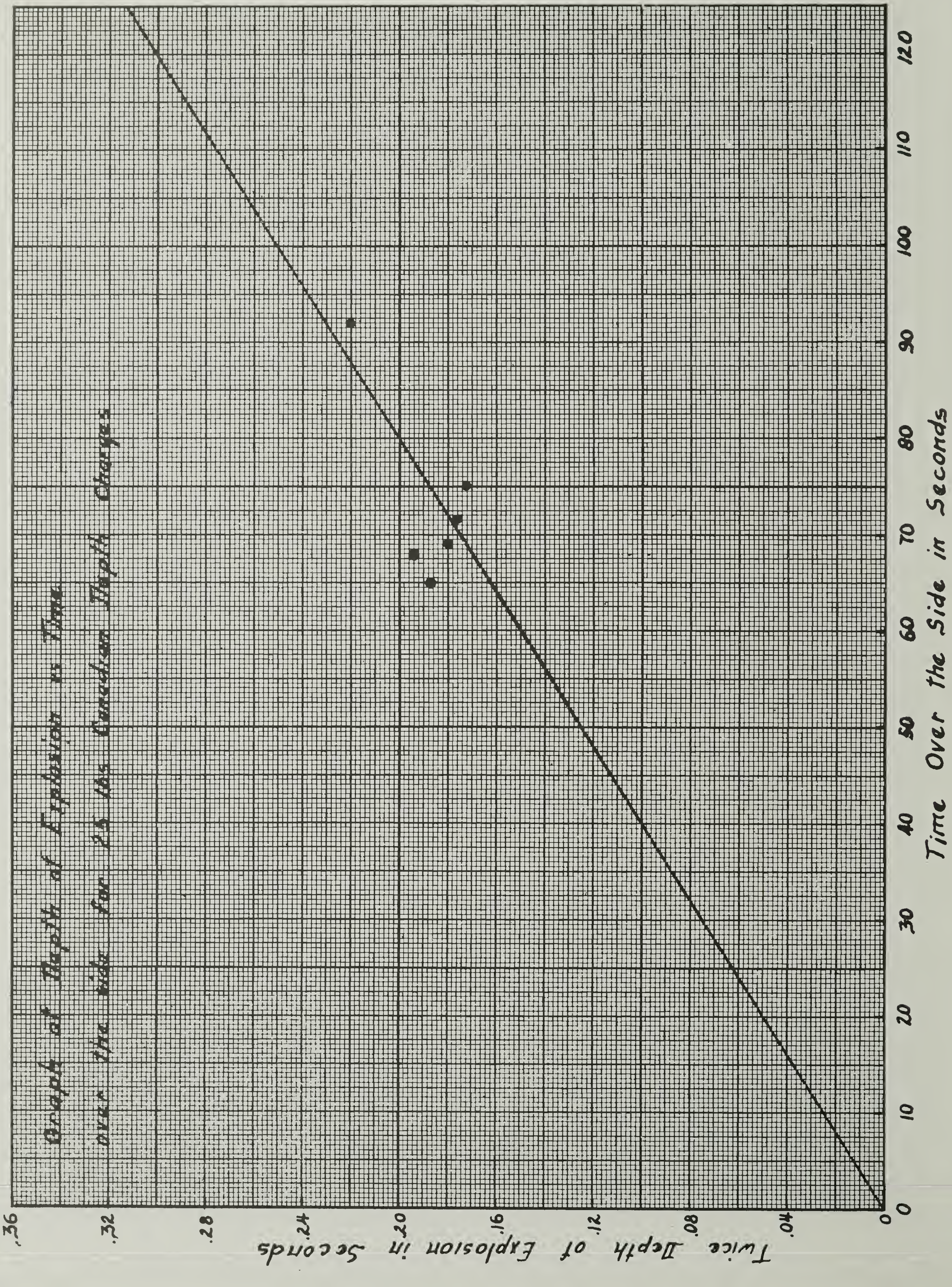

Graph of Depth of Explosion vs Time
over the side for 25 lbs Canadian Depth Charges
Time Over the Side in Seconds
0
10
20
30
40
50
60
70
80
90
100
110
120
Twice Depth of Explosion in Seconds
0
.04
.08
.12
.16
.20
.24
.28
.32
.36

Figure 9

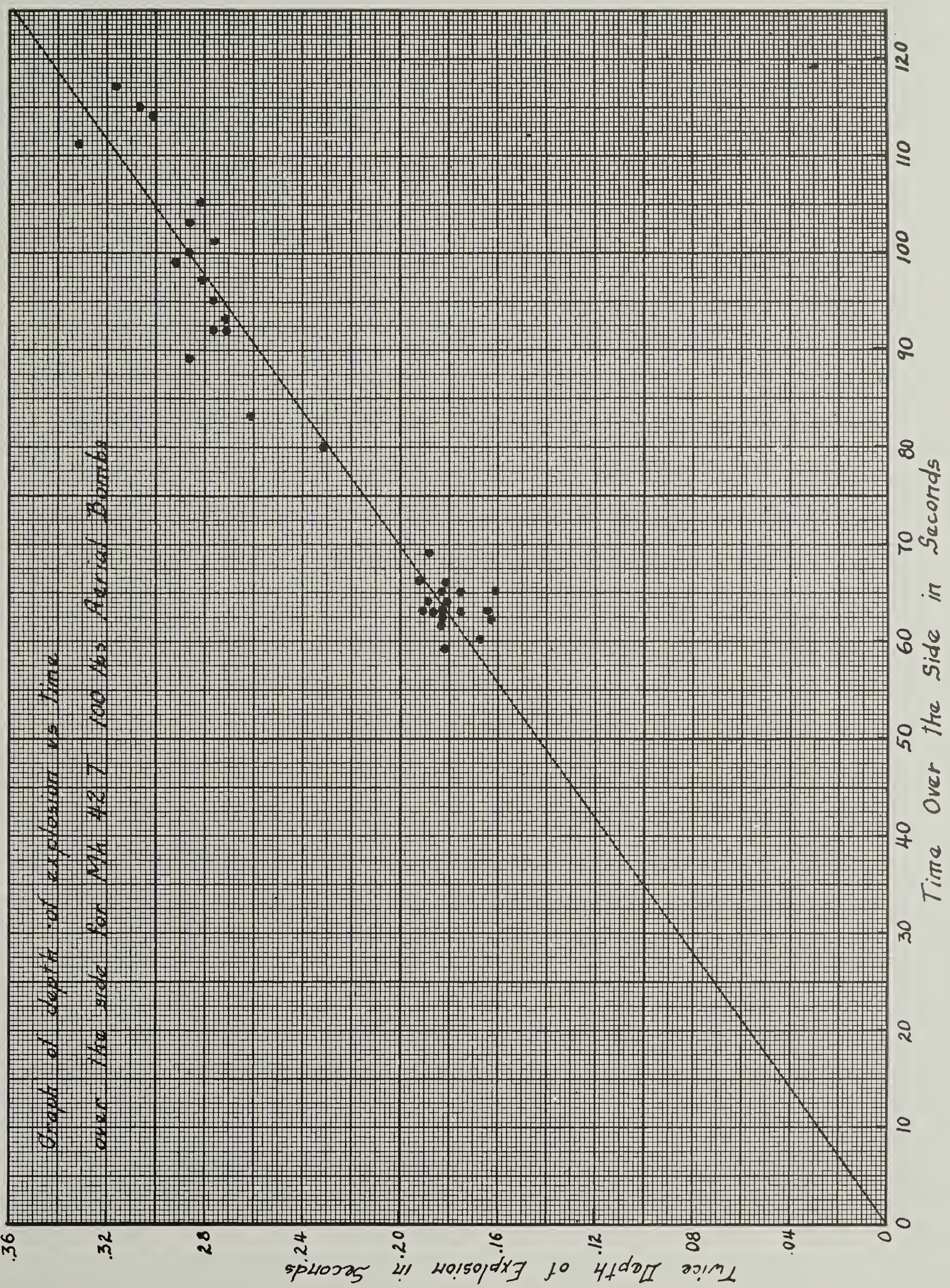
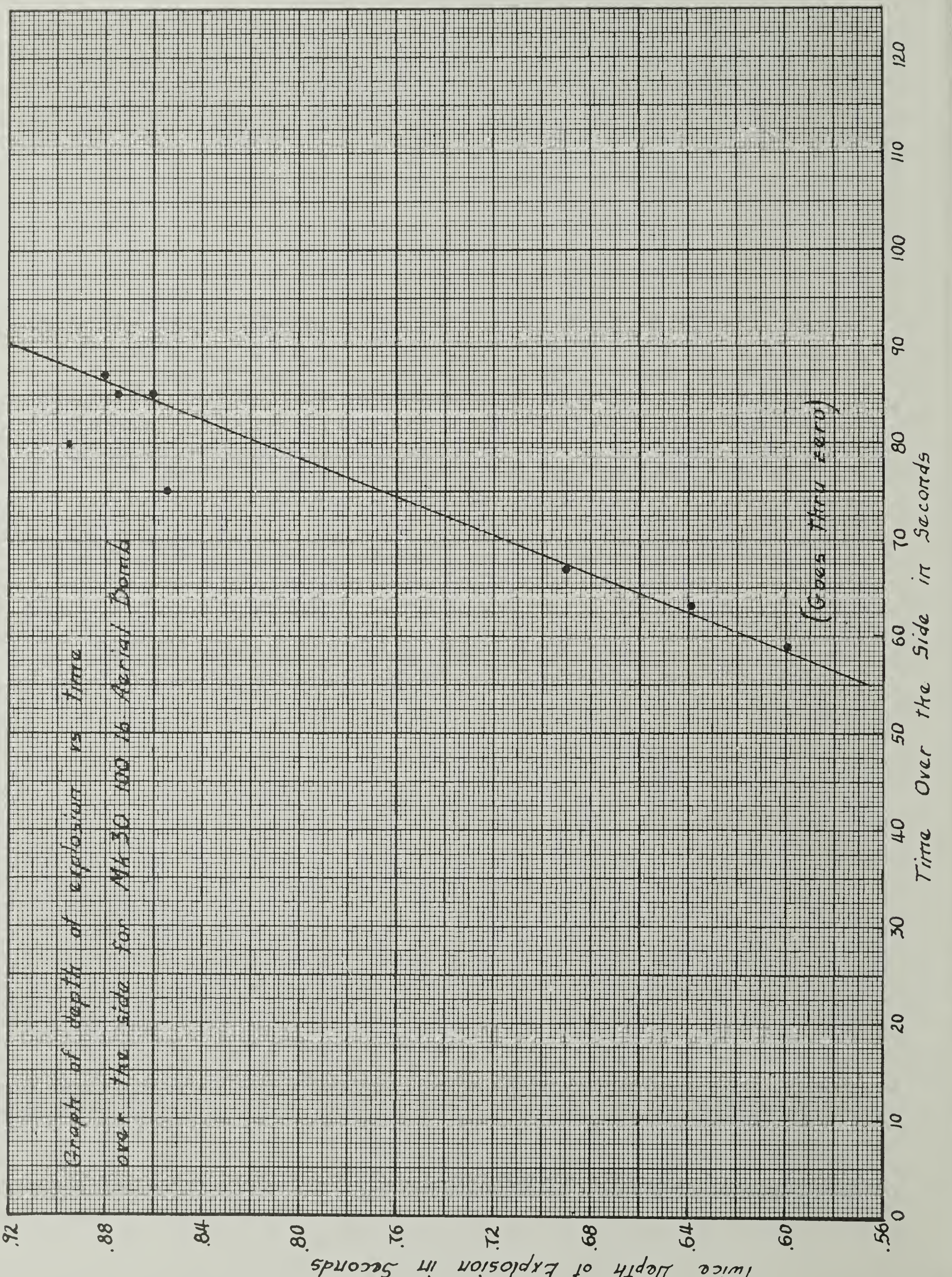

Graph of depth of explosion vs time
over the side for Mk 42 T 100 lbs Aerial Bombs
Time Over the Side in Seconds
Twice Depth of Explosion in Seconds
0
10
20
30
40
50
60
70
80
90
100
110
120
.04
.08
.12
.16
.20
.24
.28
.32
.36

Figure 10



Graph of depth of explosion vs time
over the side for Mk 30 100 lb Aerial Bomb
(Goes thru zero)
Time Over the Side in Seconds
Twice Depth of Explosion in Seconds
0
10
20
30
40
50
60
70
80
90
100
110
120
.92
.88
.84
.80
.76
.72
.68
.64
.60
.56

Figure 11

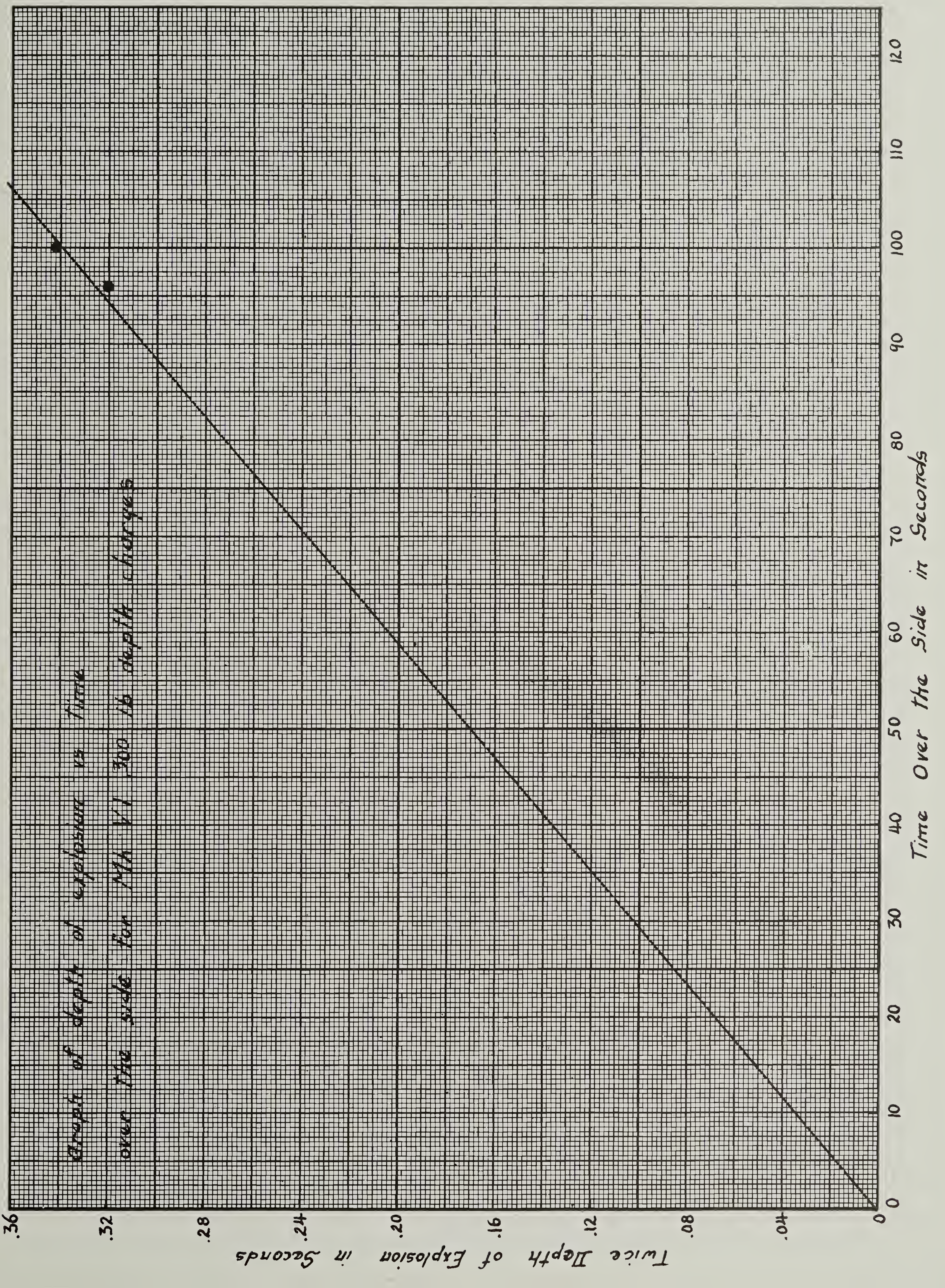

Graph of depth of explosion vs time
over the side for Mk VI 300 lb depth charges
Time Over the Side in Seconds
0
10
20
30
40
50
60
70
80
90
100
110
120
Twice Depth of Explosion in Seconds
0
.04
.08
.12
.16
.20
.24
.28
.32
.36

Figure 12

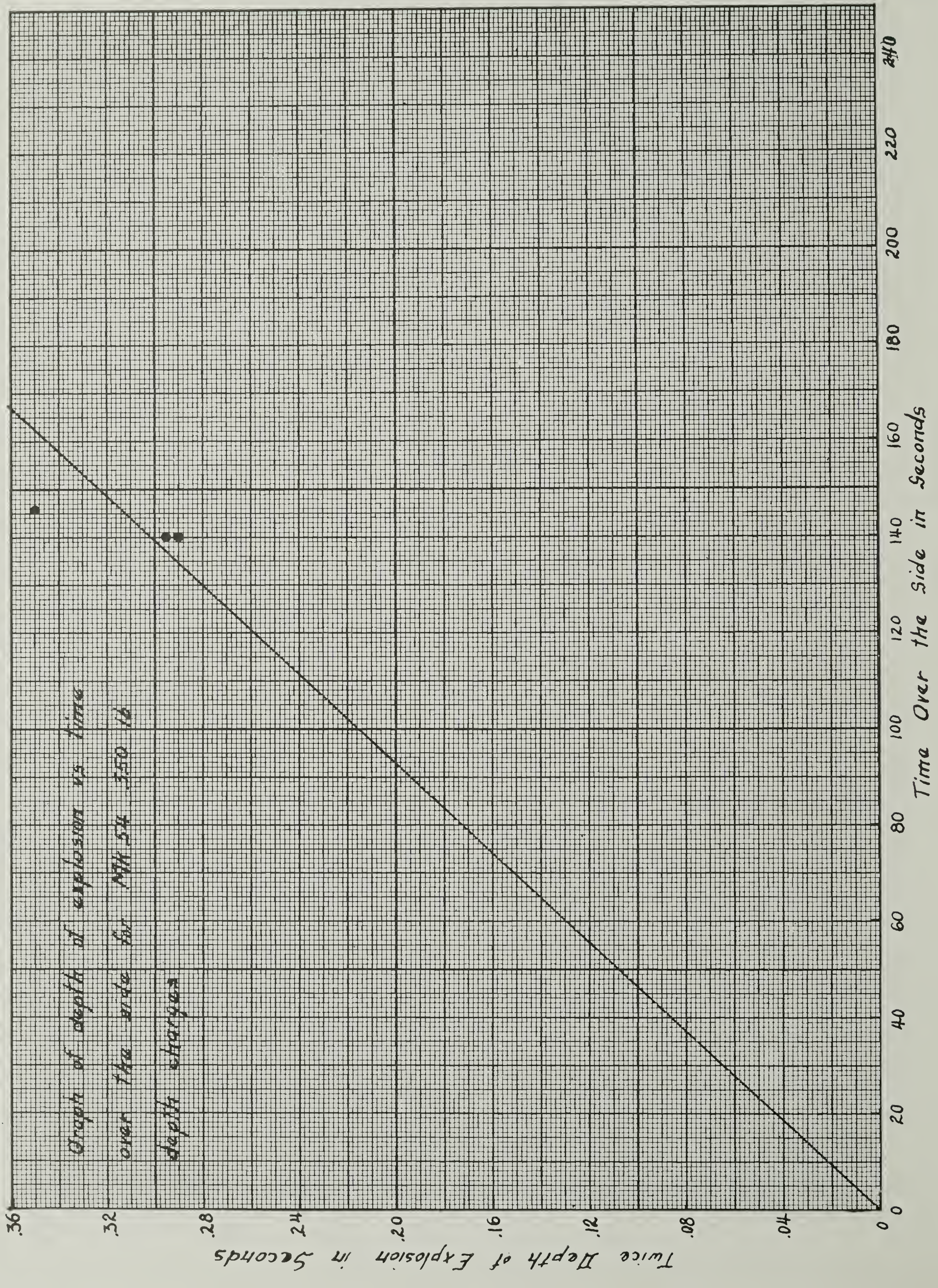

Graph of depth of explosion vs time
over the side for Mk 54 350 lb
depth charges
Time Over the Side in Seconds
0
20
40
60
80
100
120
140
160
180
200
220
240
Twice Depth of Explosion in Seconds
0
.04
.08
.12
.16
.20
.24
.28
.32
.36

Figure 15

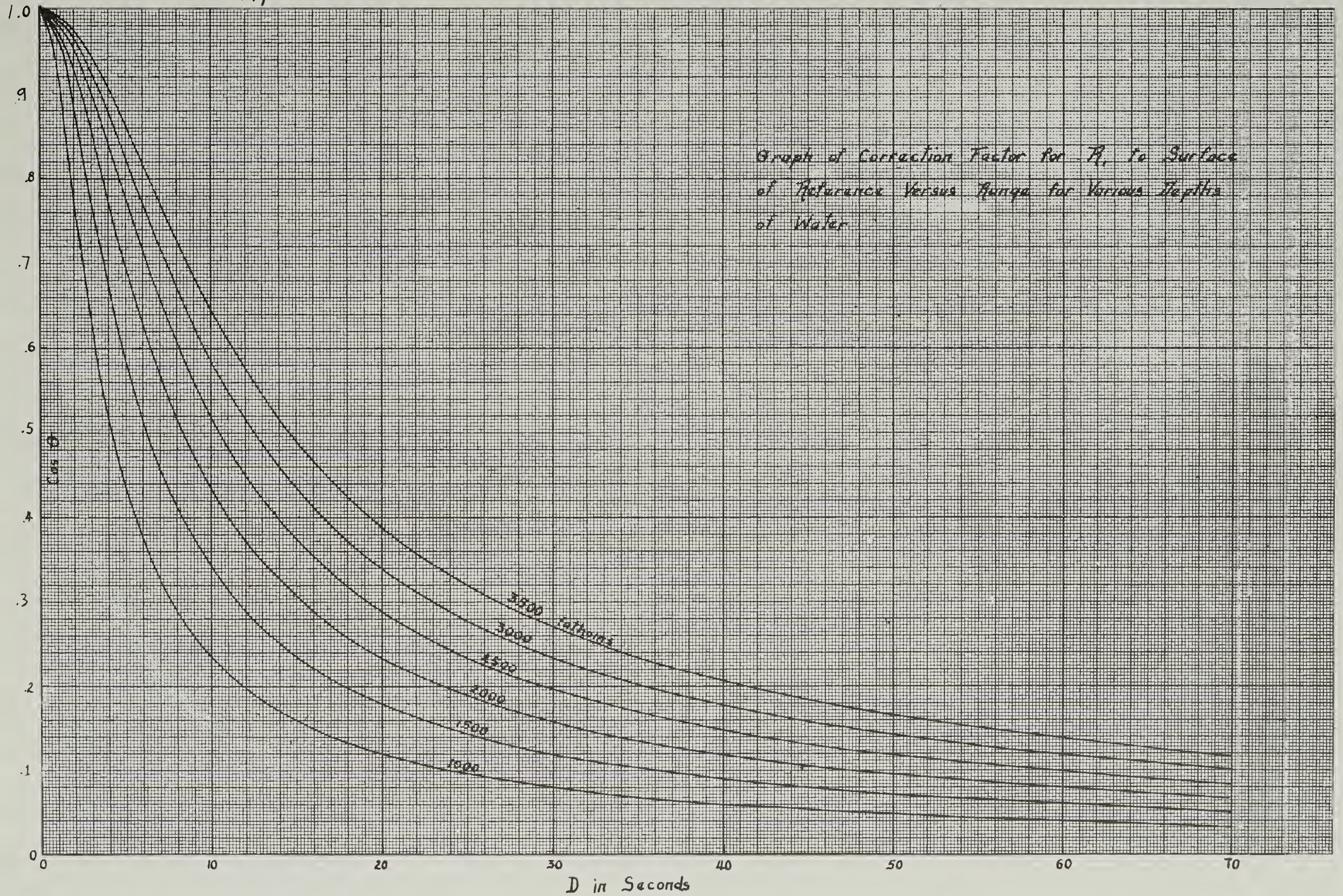

Graph of Correction Factor for R_1 to Surface of Reference Versus Range for Various Depths of Water
3500 fathoms
3000
2500
2000
1500
1000
Cos Φ
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
0
10
20
30
40
50
60
70
D in Seconds

Figure 16

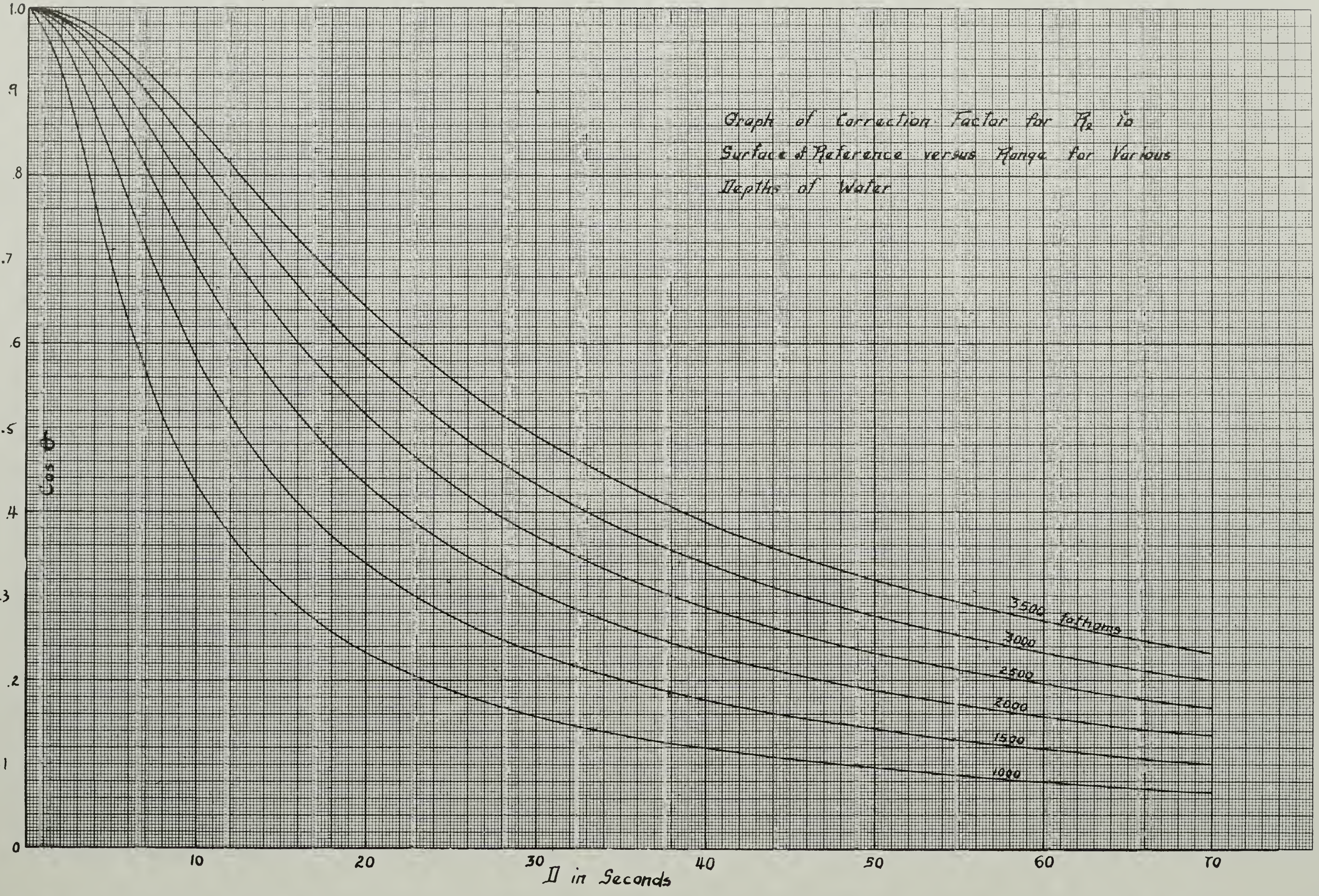
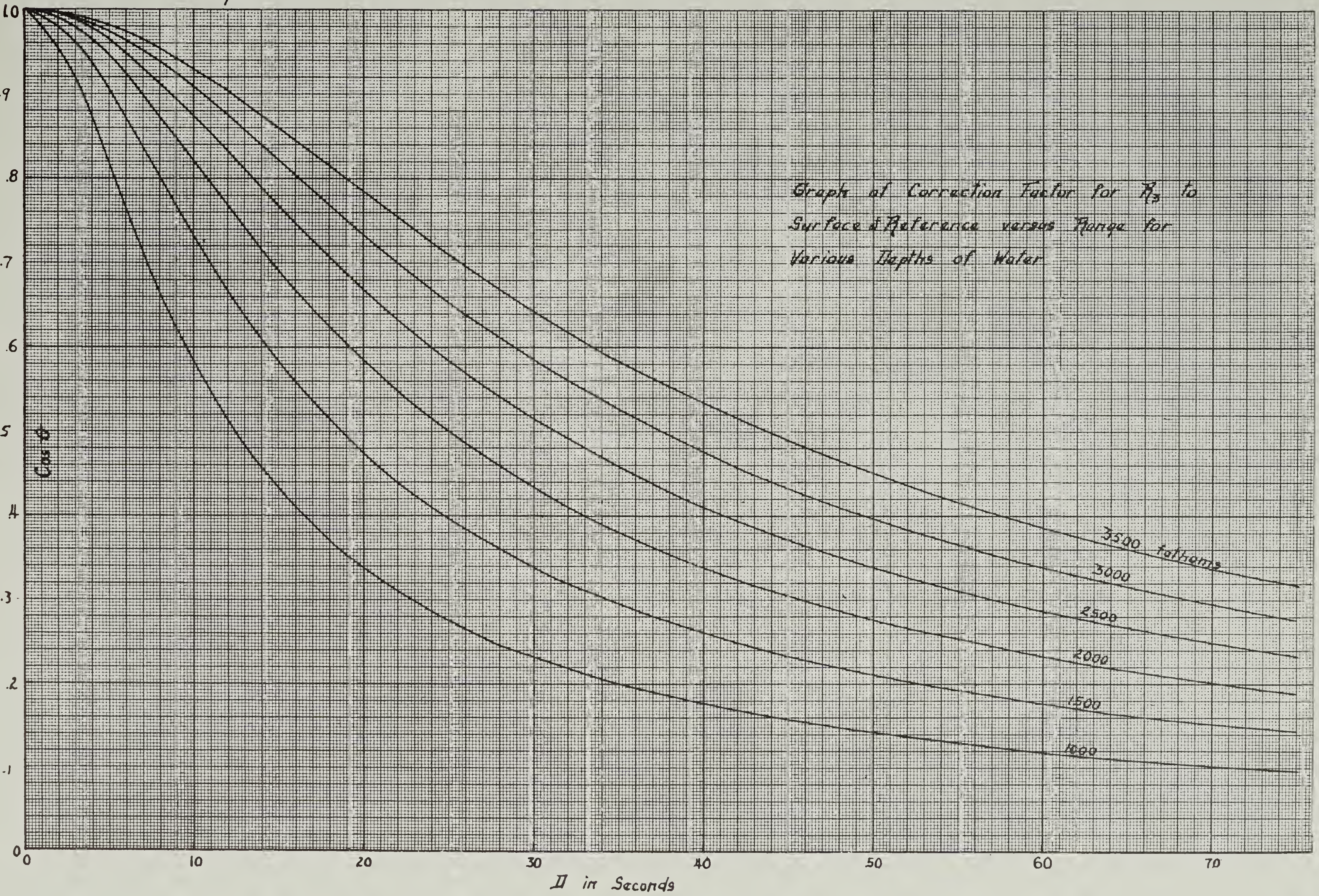

Graph of Correction Factor for R_2 to
Surface of Reference versus Range for Various
Depths of Water
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
Cos ϕ
10
20
30
40
50
60
70
Π in Seconds
3500 fathoms
3000
2500
2000
1500
1000

Figure 17



Graph of Correction Factor for R_s to Surface of Reference versus Range for Various Depths of Water
3500 fathoms
3000
2500
2000
1500
1000
Cos θ
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
0
10
20
30
40
50
60
70
Π in Seconds

Figure 18

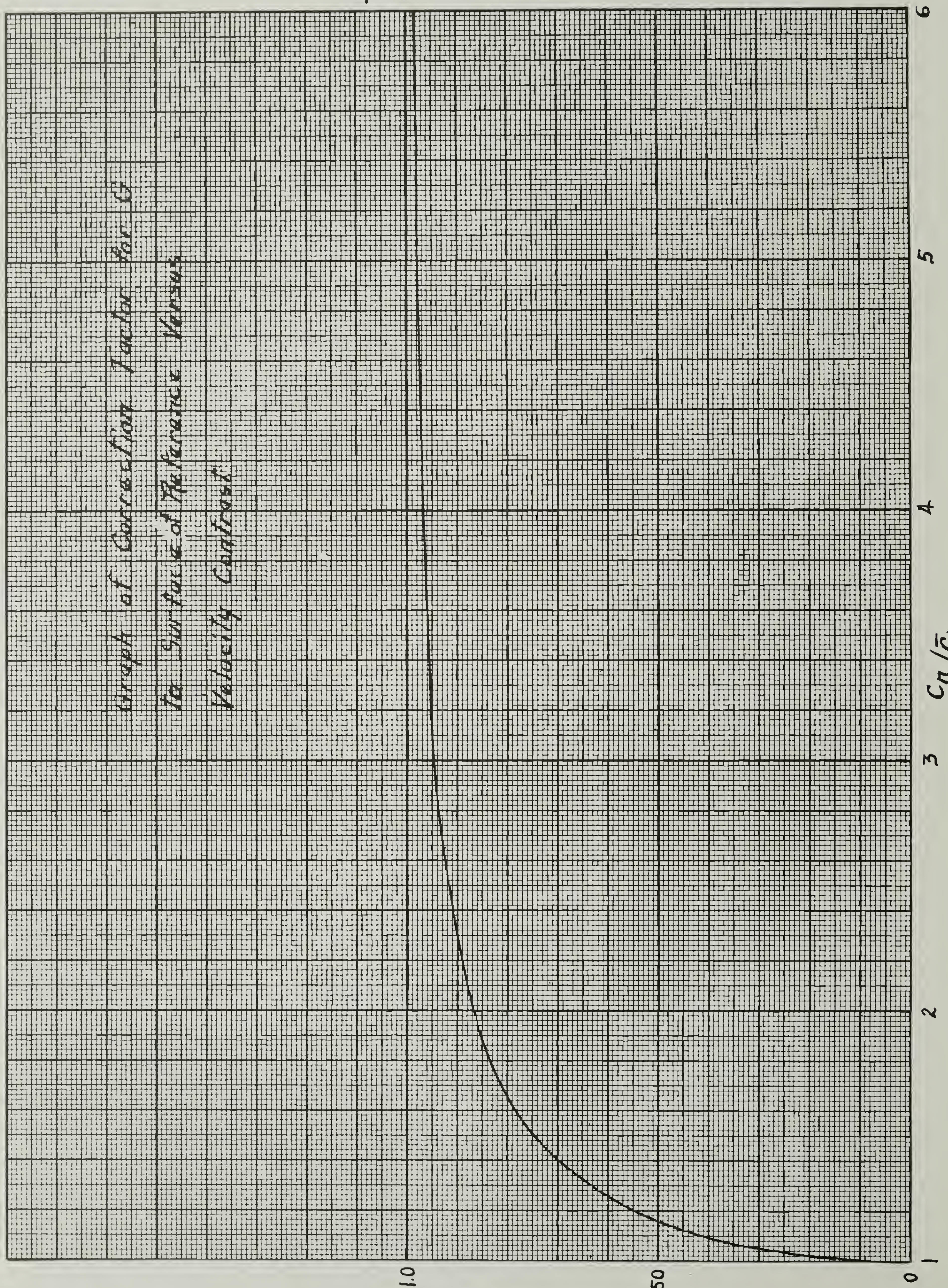
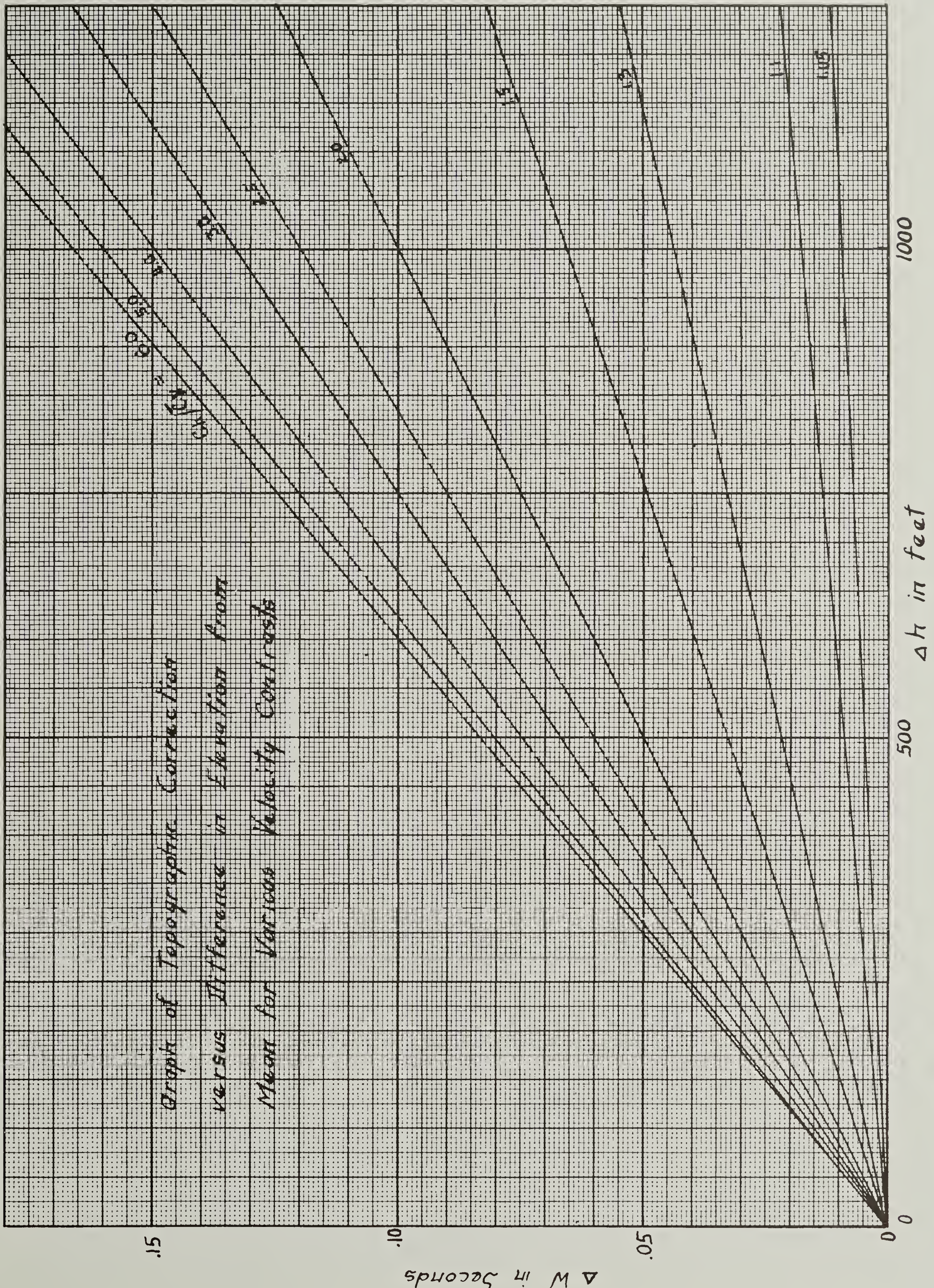
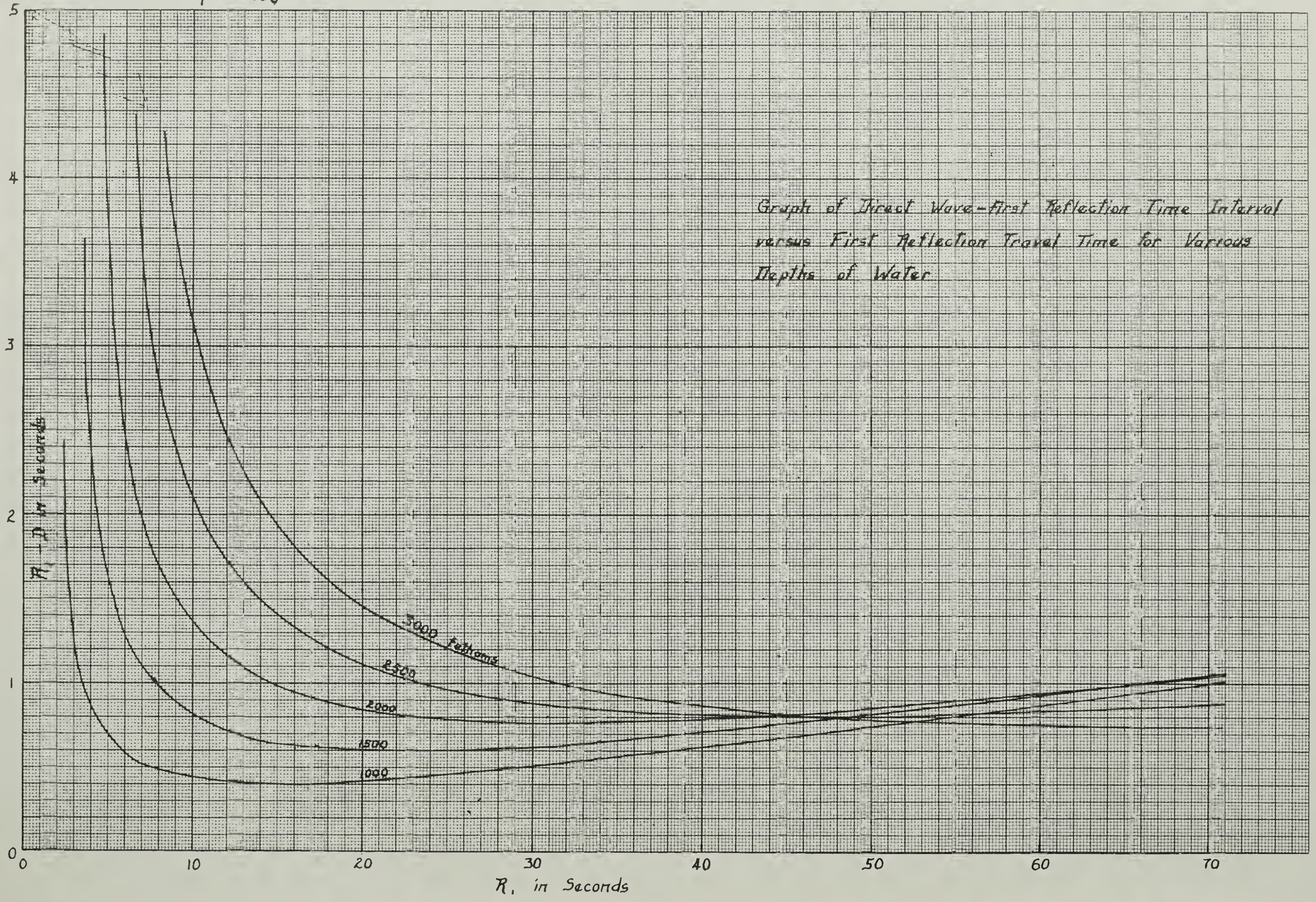

Graph of Correction Factor for C
To Surface of Reference Versus
Velocity Contrast
$C_n/\bar{C}_v$
Cos α
0
1
2
3
4
5
6
1.0
.50
0

Figure 19



Graph of Topographic Correction
versus Difference in Elevation from
Mean for Various Velocity Contrasts
Δh in feet
0
500
1000
ΔW in Seconds
0
.05
.10
.15
1.05
1.1
1.5
2.0

Figure 20


Graph of Direct Wave-First Reflection Time Interval versus First Reflection Travel Time for Various Depths of Water
3000 fathoms
2500
2000
1500
1000
R, in Seconds
R - D in Seconds
0
1
2
3
4
5
10
20
30
40
50
60
70